Contribution to ϵ'/ϵ from anomalous gauge couplings

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Abstract

Recently KTev collaboration has measured $Re(\epsilon'/\epsilon) = (28 \pm 4.1) \times 10^{-4}$ which is in agreement with early measurement from NA31. The Standard Model prediction for ϵ'/ϵ is on the lower end of the experimentally allowed range depending on models for hadronic matrix elements. In this paper we study the contributions from anomalous gauge couplings. We find that the contributions from anomalous couplings can be significant and can ehance ϵ'/ϵ to have a value closer to data.

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The parameter ϵ'/ϵ measuring direct CP violation in $K \to \pi\pi$ is a very important quantity to study [1]. A non-zero value $Re(\epsilon'/\epsilon) = (2.3 \pm 0.65) \times 10^{-3}$ was first measured by NA31 experiment [2], but E731 experiment with similar sensitivity did not confirm it [3]. This controverse is now settled with the measurement of $Re(\epsilon'/\epsilon) = (2.8 \pm 0.41) \times 10^{-3}$ by KTev experiment [4]. The parameter ϵ'/ϵ is different from the parameter ϵ which characterizes CP violation in $K^0 - \bar{K}^0$ mixing. CP violation due to mixing was first observed in 1964. Before the measurement of ϵ'/ϵ the non-zero value [5] $\epsilon = 2.266 \times e^{i\phi_\epsilon}$ with $\phi_\epsilon \approx \pi/4$ is the only laboratory experimental evidence for CP violation. Many models have been proposed to explain the non-zero value for ϵ [6]. One class of models is the superweak models [7] of CP violation which postulate that there is a new $\Delta S = 2$ interaction causing mixing and CP violation in $K^0 - \bar{K}^0$ system. In such models, there is no CP violation in $\Delta S = 1$ interaction and ϵ'/ϵ is predicted to be zero. Therefore the confirmation of non-zero ϵ'/ϵ, now, decisively rules out superweak models.

There are other models, such as the standard Kobayashi-Maskawa model (SM) [8], and the multi-Higgs model [9], which not only violate CP in $\Delta S = 2$, but also in $\Delta S = 1$ interactions. These non-superweak models with different CP violating mechanisms can explain the measured ϵ and predict, in general, different values for ϵ'/ϵ. It is clear that ϵ'/ϵ can provide further information about models for CP violation. In the SM the predicted value for ϵ'/ϵ, although in the lower end allowed by experiment as will be seen later, is not in conflict with data. More studies on the uncertainties associated with the relevant hadronic matrix elements are needed. There is also the possibility that new physics does contribute and alter the SM prediction significantly. In this paper we reanalyse the anomalous gauge coupling effects on ϵ'/ϵ in a similar way as in Ref. [10]. We find that the anomalous couplings can affect ϵ'/ϵ significantly. Using the measured value for ϵ'/ϵ, one can also constrain the allowed range for the anomalous couplings.

The CP violating $\Delta S = 1$ interaction responsible for $K \to \pi\pi$ decays in the SM is dominated by the strong penguin contributions which contribute to $I = 0$ amplitude A_0 only. The contributions due to electroweak penguins which contribute to both $I = 0$ and

$I = 2$ amplitudes A_0 and A_2, are small. However the electroweak penguins contribute to ϵ'/ϵ significantly because there is a well-known enhancement factor $1/\omega = ReA_0/ReA_2 = 22.2$ for $I = 2$ contributions [11]. For the same reason, although the contributions from anomalous couplings are similar in size to those from the electroweak penguins, these contributions having both $I = 0$ and $I = 2$ components can thus affect ϵ'/ϵ significantly.

The most general WWV interactions with the W gauge boson on-shell and invariant under $U(1)_{em}$ can be parametrized as [12]

$$\begin{aligned} L_V = & -ig_V[\kappa^V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2} W^+_{\sigma\rho} W^{-\rho\delta} V^\sigma_\delta \\ & + \tilde{\kappa}^V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}^V}{m_W^2} W^+_{\sigma\rho} W^{-\rho\delta} \tilde{V}^\sigma_\delta \\ & + g_1^V (W^{+\mu\nu} W^-_{\mu\nu} - W^+_\mu W^{-\mu\nu}) V_\nu + g_4^V W^+_\mu W^-_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\ & + g_5^V \epsilon_{\mu\nu\alpha\beta} (W^{+\mu} \partial^\alpha W^{-\nu} - \partial^\alpha W^{+\mu} W^{-\nu}) V^\beta], \end{aligned} \tag{1}$$

where $W^{\pm\mu}$ are the W boson fields; V can be the γ or Z fields; $W_{\mu\nu}$ and $V_{\mu\nu}$ are the W and V field strengths, respectively; and $\tilde{W}(\tilde{V})_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta} W(V)^{\alpha\beta}/2$. The terms proportional to κ, λ, and $g_{1,5}$ are CP conserving and $\tilde{\kappa}$, $\tilde{\lambda}$, and g_4^Z are CP violating. Our convention is that for $V = \gamma$, $g_V = e$ and for $V = Z$, $g_V = g\cos\theta_W$. g_1^γ defines the W boson charge and is always normalized to 1. In the SM at the tree level, κ^V and g_1^Z are equal to 1, and all others are zero. We refer $\Delta\kappa^V = \kappa^V - 1$, $\Delta g_1^Z - 1$, $\tilde{\kappa}^V$, $\tilde{\lambda}$, g_4^V and g_5^V as anomalous couplings.

With non-zero anomalous couplings, at the energy scale $\mu = m_W$ beside the SM effective Hamiltonian H_{SM} for $\Delta S = 1$ interaction, there are additional contributions [10]

$$\begin{aligned} H_{AC} = & \frac{G_F \alpha_{em}}{2\sqrt{2}\pi} \sum_{i=u,c,t} V_{id} V^*_{is} \sum_{q=u,d} [Q_q H(x_i)_A \bar{s}\gamma_\mu (1-\gamma_5) d \bar{q}\gamma^\mu q \\ & + \cot^2\theta_W F(x_i)_A \bar{s}\gamma_\mu(1-\gamma_5) d\bar{q}\gamma^\mu (Q_q \sin^2\theta_W - T^3 \frac{1-\gamma_5}{2}) q], \end{aligned} \tag{2}$$

where Q_q is the charge of q quark, $x_i = m_i^2/m_W^2$, T_3 is the isospin operator with eigenvalues $1/2$ and $-1/2$ for u and d respectively, and

$$\begin{aligned} H(x)_A = & \Delta\kappa^\gamma \frac{x}{4} \ln\frac{\Lambda^2}{m_W^2} + \lambda^\gamma [\frac{x(1-3x)}{2(1-x)^2} - \frac{x^3}{(1-x)^3} \ln x], \\ F(x)_A = & -\Delta g_1^Z \frac{3}{2} x \ln\frac{\Lambda^2}{m_W^2} + g_5^Z [\frac{3x}{1-x} + \frac{3x^2}{(1-x)^2} \ln x]. \end{aligned} \tag{3}$$

In obtaining H_{AC} we have used unitary gauge and introduced a momentum cut-off Λ for terms which are divergent in loop integrals. Note that H_A and F_A are proportional to internal quark mass squared. The dominant contribution is therefore from t quark in the loop. Also to the leading order H_{AC} does not depend on CP violating couplings $\tilde{\kappa}^\gamma$, $\tilde{\lambda}^\gamma$ and g_4^Z. Contributions from these couplings and $\Delta\kappa^Z$ are suppressed by factors of $O((m_{d,s}^2, m_K^2)/m_W^2))$ and are neglected. The source of CP violation for $K \to \pi\pi$ decays with anomalous couplings is therefore the same as in the SM.

At an energy scale μ lower than m_W the effective Hamiltonian H_{eff} for $\Delta S = 1$ interaction receives important QCD corrections. H_{eff} is usually parametrized as [13]

$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* \sum_{i=1,10} C_i(\mu) O_i(\mu), \tag{4}$$

where $C_i(\mu) = z_i(\mu) + \tau y_i(\mu)$, $\tau = -V_{td}V_{ts}^*/V_{ud}V_{us}^*$, and

$$\begin{aligned}
&O_1 = \bar{s}\gamma_\mu(1-\gamma_5)d\bar{u}\gamma^\mu(1-\gamma_5)u, \quad O_2 = \bar{s}\gamma_\mu(1-\gamma_5)u\bar{u}\gamma^\mu(1-\gamma_5)d, \\
&O_{3,5} = \bar{s}\gamma_\mu(1-\gamma_5)d\sum_q \bar{q}\gamma^\mu(1\mp\gamma_5)q, \quad O_{4,6} = \bar{s}_\alpha\gamma_\mu(1-\gamma_5)d_\beta\sum_q \bar{q}_\beta\gamma^\mu(1\mp\gamma_5)q_\alpha, \\
&O_{7,9} = \frac{3}{2}\bar{s}\gamma_\mu(1-\gamma_5)d\sum_q Q_q\bar{q}\gamma^\mu(1\pm\gamma_5))q, \quad O_{8,10} = \frac{3}{2}\bar{s}_\alpha\gamma_\mu(1-\gamma_5)d_\beta\sum_q Q_q\bar{q}_\beta\gamma^\mu(1\pm\gamma_5)q_\alpha.
\end{aligned} \tag{5}$$

In the above we have neglected the dipole interactions which have been shown to have negligible contributions to ϵ'/ϵ [14].

The boundary conditions of the Wilson coefficients (WC) needed for renormalization running from m_W to μ for the SM can be found in Ref. [13] and the ones due to anomalous couplings are

$$\begin{aligned}
y_3^{AC}(m_W) &= -\frac{\alpha_{em}}{24\pi}F(x_t)\cot^2\theta \\
y_7^{AC}(m_W) &= -\frac{\alpha_{em}}{6\pi}\left[H(x_t)_A + \sin^2\theta_W\cot^2\theta_W F(x_t)_A\right], \\
y_9^{AC}(m_W) &= -\frac{\alpha_{em}}{6\pi}[H(x_t)_A - \cos^2\theta_W\cot^2\theta_W F(x_t)_A].
\end{aligned} \tag{6}$$

In the SM the WCs y_i^{SM} have been obtained at the next-leading order in QCD. We will use the values,

$$
\begin{aligned}
&(y_3^{SM}, y_4^{SM}, y_5^{SM}, y_6^{SM}, y_7^{SM}/\alpha_{em}, y_8^{SM}/\alpha_{em}, y_9^{SM}/\alpha_{em}, y_{10}^{SM}/\alpha_{em}) \\
&= (3.78, -5.97, 1.60, -9.94, -1.95, 20.9, -175, 80.6) \times 10^{-2},
\end{aligned} \tag{7}
$$

obtained in Ref. [1] in the VH scheme with $\alpha_s = 0.119$, $m_t(m_t) = 167$ GeV, $m_b(m_b) = 4.4$ GeV, and $m_c(m_c) = 1.4$ GeV at $\mu = 1$ GeV.

When the anomalous couplings are included, the values for the WCs y_i will change. We will use the leading order QCD results for y_i^{AC} from the anomalous couplings which are sufficient for the purpose of illustrating how the anomalous couplings affect the SM prediction. At $\mu = 1$ GeV, anomalous couplings will generate non-zero $y_{7,8,9,10}^{AC}$ as well as $y_{3,4,5,6}^{AC}$. We find that the contributions to ϵ'/ϵ from $y_{3,4,5,6}^{AC}$ are negligibly small. We will only write down the values for $y_{7,8,9,10}^{AC}$. Numerically we have

$$
\begin{aligned}
y_7^{AC}/\alpha_{em} &= -0.243\Delta\kappa^\gamma - 0.039\lambda^\gamma + 1.21 g_1^Z - 0.13 g_5^Z, \\
y_8^{AC}/\alpha_{em} &= -0.203\Delta\kappa^\gamma - 0.033\lambda^\gamma + 0.98 g_1^Z - 0.11 g_5^Z, \\
y_9^{AC}/\alpha_{em} &= -0.353\Delta\kappa^\gamma - 0.057\lambda^\gamma - 5.95 g_1^Z + 0.64 g_5^Z, \\
y_{10}^{AC}/\alpha_{em} &= 0.140\Delta\kappa^\gamma + 0.023\lambda^\gamma + 2.34 g_1^Z - 0.25 g_5^Z.
\end{aligned} \tag{8}
$$

In the above we have used a cut-off $\Lambda = 1$ TeV for terms proportional to $\Delta\kappa^\gamma$ and g_1^Z. The above confirms the calculation in Ref. [10].

Theoretical analyses for ϵ'/ϵ are conventionally carried out in terms of the isospin amplitudes A_I for $K \to \pi\pi$. Expressing ϵ'/ϵ in terms of A_I, y_i, KM factor $Im(V_{td}V_{ts}^*)$ and hadronic matrix elements $< O_i >_I = < \pi\pi|O_i|K >_I$, we have

$$
\begin{aligned}
\frac{\epsilon'}{\epsilon} &= e^{i(\pi/2+\delta_2-\delta_0)} \frac{\omega}{\sqrt{2}\epsilon} \left(\frac{ImA_2}{ReA_2} - \frac{ImA_0}{ReA_0} \right) \\
&= e^{i(\pi/2+\delta_2-\delta_0-\phi_\epsilon)} \frac{G_F\omega}{2|\epsilon|ReA_0} Im(V_{td}V_{ts}^*)(\Pi_0^{SM} - \frac{1}{\omega}\Pi_2^{SM})(1+\Delta) \\
\Delta &= \frac{\Pi_0^{AC} - \Pi_2^{AC}/\omega}{\Pi_0^{SM} - \Pi_2^{SM}/\omega}, \\
\Pi_0^k &= \frac{1}{\cos\delta_0} \sum_i y_i^k Re < O_i >_0 (1 - \Omega_{\eta+\eta'}), \quad \Pi_2^k = \frac{1}{\cos\delta_2} \sum_i y_i^k Re < O_i >_2,
\end{aligned} \tag{9}
$$

where $\delta_0 = 34.2^0 \pm 2.2^0$, $\delta_2 = -6.9^0 \pm 0.2^0$ [15] are the final state interaction phases of the amplitudes $A_{0,2}$, and $\Omega_{\eta+\eta'} = 0.25 \pm 0.10$ [11,16] is correction due to isospin breaking mixing

between pion and etas. Δ is a measure of the contribution from anomalous couplings with respect to that from the SM.

To obtain the prediction for ϵ'/ϵ, one needs to evaluate the hadronic matrix elements $< O_i >_{0,2}$. This is the most difficult part of the calculation which we will not attempt to do here. We will take the values listed in Table 6 of Ref. [1] which are obtained in Ref. [17] using chiral quark model. In our numerical calculation, we use: $\delta_0 = 34.2^0$, $\delta_2 = -6.9^0$, $\omega = 1/22.2$, $\Omega_{\eta+\eta'} = 0.25$. We have for the SM prediction

$$Re\left(\frac{\epsilon'}{\epsilon}\right) \approx 12Im(V_{td}V_{ts}^*) \approx 12\eta|V_{us}||V_{cb}|^2, \tag{10}$$

where η is the CP violating parameter in the Wolfenstein parameterization. We find that the dominant contributions are from terms proportional to y_6^{SM} and y_8^{SM} with the one from y_8^{SM} cancels part of the one from y_6^{SM}.

The magnitude of ϵ'/ϵ depends on the hadronic parameters mentioned before and also on the KM factor $Im(V_{td}V_{ts}^*) \approx \eta|V_{us}||V_{cb}|^2$ which is constrained from various experimental measurements. We use: $|V_{us}| = 0.2196 \pm 0.0023$, $|V_{cb}| = 0.0395 \pm 0.0017$ [5], and $\eta = 0.381^{+0.061}_{-0.058}$ obtained in Ref. [18]. We note that the sign for ϵ'/ϵ is positive in agreement with experiment. ϵ'/ϵ is predicted to be

$$Re\left(\frac{\epsilon'}{\epsilon}\right) = 1.57^{+0.35}_{-0.34} \times 10^{-3}. \tag{11}$$

Here only errors due to KM elements and $\Omega_{\eta+\eta'}$ are included. This range is lower than the central experimental data which is a potential problem for the SM. However we note that even if we take the above theoretical value seriously, there is an overlap between the predicted value and the grand average value $Re(\epsilon'/\epsilon) = (2.18 \pm 0.30) \times 10^{-3}$ of NA31, E731 and KTev data at 1σ level. When possible errors [2,17,19] due to various parameters such as s quark mass and the bag factors B_i are taken into account, the predicted value for ϵ'/ϵ can be larger [1]. It is too early to call for new physics. Nevertheless, contributions from new physics can dramatically change the SM prediction [20]. We now present our analysis for the contributions from anomalous couplings. We find indeed that the contributions from anomalous couplings can enhance ϵ'/ϵ and easy the above potential problem in the SM.

The contributions to ϵ'/ϵ due to anomalous couplings from $I = 0$ amplitude are small, but contributions from $I = 2$ amplitude through possible large value for y_8^{AC} can be significantly larger. This can be seen by comparing the values of y_8^{AC} with the SM value $y_8^{SM} = 0.209\alpha_{em}$. Using the same hadronic matrix elements used for the SM calculation, we obtain

$$Re\left(\frac{\epsilon'}{\epsilon}\right) \approx 12Im(V_{td}V_{ts}^*)(1 + 0.69\Delta\kappa^\gamma + 0.11\lambda^\gamma - 2.88g_1^Z + 0.31g_5^Z). \quad (12)$$

From the above equation we see that the contributions from anomalous couplings can be large and can also have the same sign as in the SM, in which case the predicted value for ϵ'/ϵ is enhanced. $\Delta\kappa^\gamma < 0$, $\lambda^\gamma < 0$, $g_1^Z > 0$ and $g_5^Z < 0$ reduce the contribution total value of ϵ'/ϵ. They are therefore not favored. With the opposite signs, the total contribution to ϵ'/ϵ is enhanced.

It is interesting to note that even in the presence of the anomalous couplings the constraints on the KM elements do not change, because the anomalous couplings do not contribute to the processes used for the fitting. We can use the same range for the KM factor $Im(V_{td}V_{ts}^*)$. The magnitudes of the contributions to ϵ'/ϵ depend on the sizes of the anomalous couplings. It is easily seen that ϵ'/ϵ is most sensitive to g_1^Z. Phenomenological implications of the anomalous couplings have been studied for high energy collider physics [21,22], low energy flavor conserving processes [23], and flavor changing rare decays [24]. Since $K \to \pi\pi$ decays are flavor changing decays, we should use constraints from flavor changing processes for direct comparison. The conservative allowed ranges at 95% C.L, with only one anomalous coupling to be non-zero in a given process, contains the following ranges: $\Delta\kappa^\gamma : -0.36 \sim 0.4$, $\lambda^\gamma : -1 \sim 1$, $\Delta g_1^Z : -0.5 \sim 0.1$ and $g_5^Z : -1 \sim 2$. Within these ranges, the anomalous coupling can enhance the contribution to ϵ'/ϵ by a factor as large as 2.5 from g_1^Z contribution which can significantly easy the potential problem in the Standard Model. If several anomalous couplings simultaneously contribute with the right combination, even larger contribution to ϵ'/ϵ can be obtained. Taking the theoretical calculations for the hadronic matrix elements used here seriously and require that the prediction and data for ϵ'/ϵ to have overlap, we find that $\Delta\kappa^\gamma < 0$, $\lambda^\gamma < 0$, $g_1^Z > 0$ and $g_5^Z < 0$ are approximately

ruled out at 1σ and 2σ levels for the averaged and KTev values for ϵ'/ϵ, respectively.

In conclusion we have studied the contributions of anomalous gauge couplings to ϵ'/ϵ. We find that within the allowed ranges, the anomalous couplings can enhance the SM prediction for ϵ'/ϵ by a factor as large as 2.5. This enhancement factor can help easy potential problem in the SM which predicts a ϵ'/ϵ lower than the experimental data from some model calculations. $\Delta\kappa^\gamma$, λ^γ, g_5^Z less than zero and g_1^Z larger than zero are disfavored.

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